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1 Scope of the Research

This was an observing-intensive investigation into the newly discovered regions of the solar system beyond Neptune. The research was focussed on the use of unique imaging facilities on telescopes atop Mauna Kea, Hawaii, although other observatories (in Arizona and Chile) were also occasionally used.

- We secured about 20 nights of telescope time per year for our "Medium Depth Wide Area" survey (*JLC96*). In this, we covered 5 sq. deg. of sky to apparent red magnitude 24.2. We used a high quantum efficiency Tektronix 2048x2048 CCD for all observations in this program.
- We secured observing time at the UH 2.2 meter for testing the suitability of a much larger array CCD camera for survey work (an 8192x8192 pixel device).
- We obtained observing runs at the twin Schmidt telescopes of Kitt Peak National Observatory and Cerro-Tololo InterAmerican Observatory in order to assess the number of bright Kuiper Belt objects, Centaurs and gas giant Trojans.

2 Major Results

During the period of this proposal, we have:

- Brought the total number of known trans-Neptunian objects to 32. Most of these objects were discovered using the University of Hawaii 2.2 m telescope. The evidence for the existence of a large population of 100 km to 200 km sized bodies beyond Neptune (the so-called "Kuiper Belt") is now compelling.
- Estimated the number of objects in the $30 \leq R \leq 50$ AU heliocentric distance range with diameters $D \geq 100$ km to be $N \sim 70,000$ (JLC 96). This huge population dwarfs the number of comparably large main-belt asteroids by a factor of several hundreds.
- Estimated the total mass in the Kuiper Belt as $\approx 0.1 M_{\text{Earth}}$ (JLC 96).

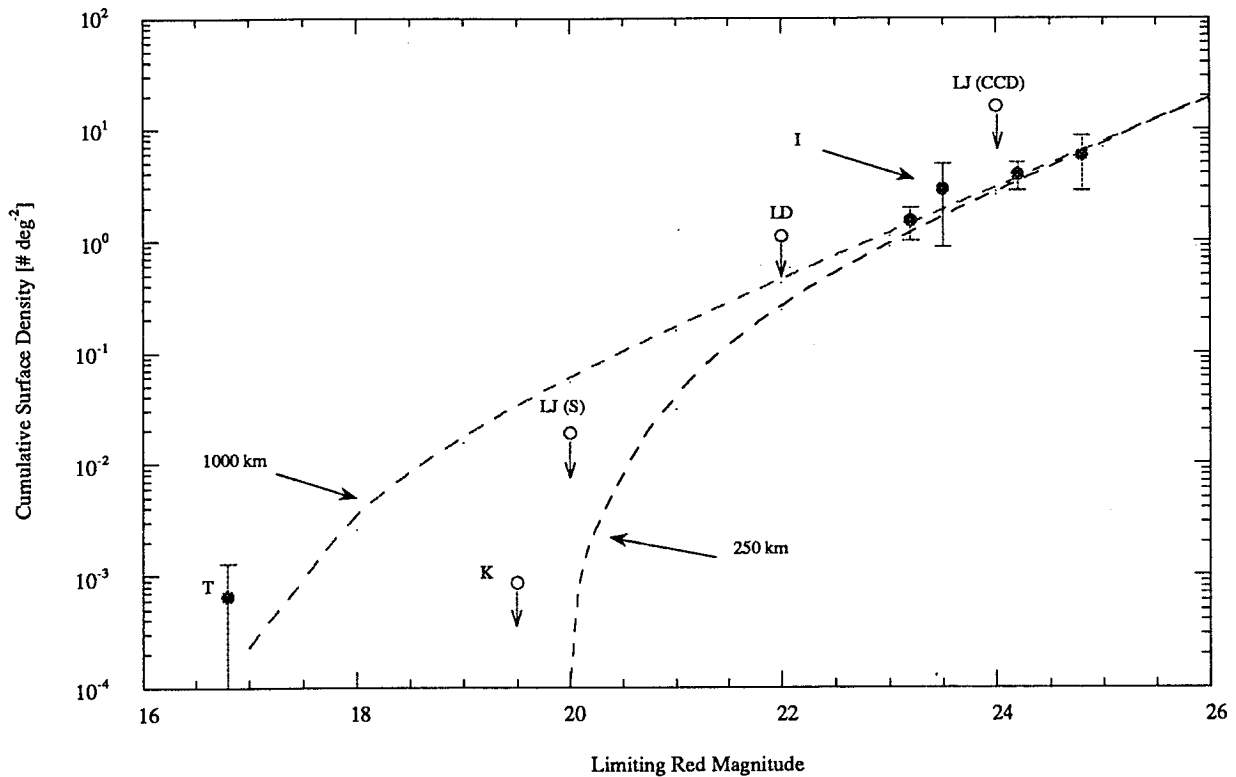


Figure 1 Sky-plane surface densities of the Kuiper Belt, from Table 6. Filled circles with error bars denote detections, while empty circles with downward pointing arrows mark upper limits. Key: T = Tombaugh (1961), K = Kowal (1989), LJ(S) and LJ(CCD) are the Schmidt and CCD surveys of Luu and Jewitt (1988), LD = Levison and Duncan (1990), I = Irwin *et al.* (1995) and C = Cochran *et al.* (1995). The two dashed curves show the expected surface densities for power law models in which the maximum object diameter is 1000 km and 250 km, as marked. The right hand axis shows the total number of objects brighter than m_R assuming ecliptic area = 10^4 deg^2 .

- Determined the magnitude-frequency relation for the Kuiper Belt (Figure 1). The observed relation is compatible with differential power law size distributions having index $q \approx -2$ to -3 .

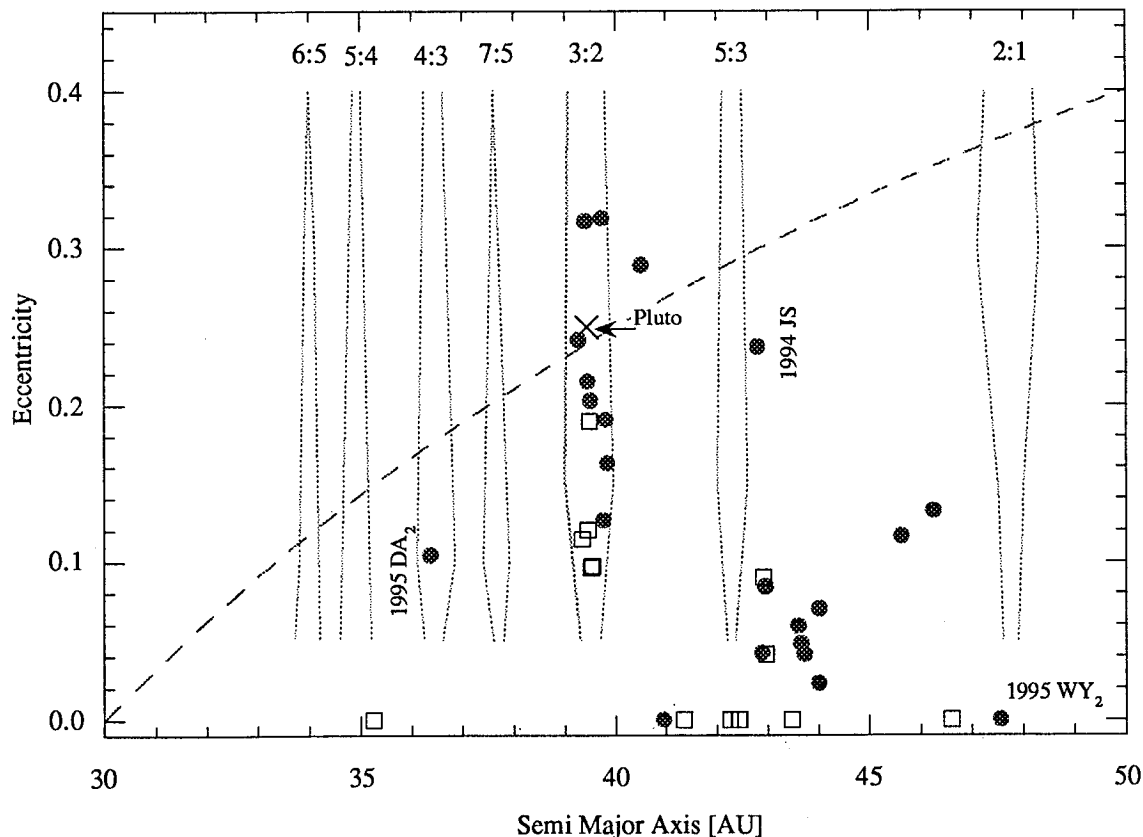


Figure 2 Semi-major axis vs. orbital eccentricity of the Kuiper Belt objects. Higher quality orbital elements computed from astrometry taken over $N > 1$ opposition (circles) are distinguished from lower quality elements determined from astrometry within the discovery year (diamonds). Locations of mean motion resonances are marked and labelled (from Malhotra 1995). The dashed line marks perihelion distance $q = 30$ AU. Objects above the line are Neptune-crossing.

- We discovered that up to 40% of the Kuiper Belt objects are in or near the 3:2 mean-motion resonance with Pluto (JL95; JLC96; Jewitt and Luu 1996; 1997; see Figure 2). These "Plutinos" suggest to us that Pluto is the largest object in a family that numbers many 10's of thousands of dynamically related bodies, rather than a peculiarly small and eccentric outer planet. Viewed by some as an unseemly demotion of Pluto from planet-hood, we see this change in perspective as an exciting opportunity to understand the origin and history of this body. Some of the models proposed to explain the high populations of resonances also make predictions (e.g. the ratio of populations of the 3:2 and 2:1 resonances) that will be amenable to observational tests. Thus, we

see real hope that the origin of Plutinos will soon be understood.

- We measured the width of the Kuiper Belt. The width is a measure of the intrinsic velocity dispersion in the Belt, and thus acts as an indicator of the collisional environment. In the plane of the sky, the Kuiper Belt subtends $10^\circ \pm 1^\circ$ FWHM. Consideration of the effects of observational selection shows that this is a lower limit to the true thickness of the belt. The largest measured inclinations are near 30° . Objects located in dynamical resonances have (on average) slightly larger inclinations than those outside resonance (Figure 3). However, published theories predict inclination distributions within the 3:2 resonance that are narrower than observed. The origin of this discrepancy is unclear. The wide inclination distributions measured both in and out of resonances show that the impact velocities in the Belt are exceed 1 km/s. Therefore, collisions tend to be erosive rather than agglomerative, at least in the inner parts of the Belt studied to date.

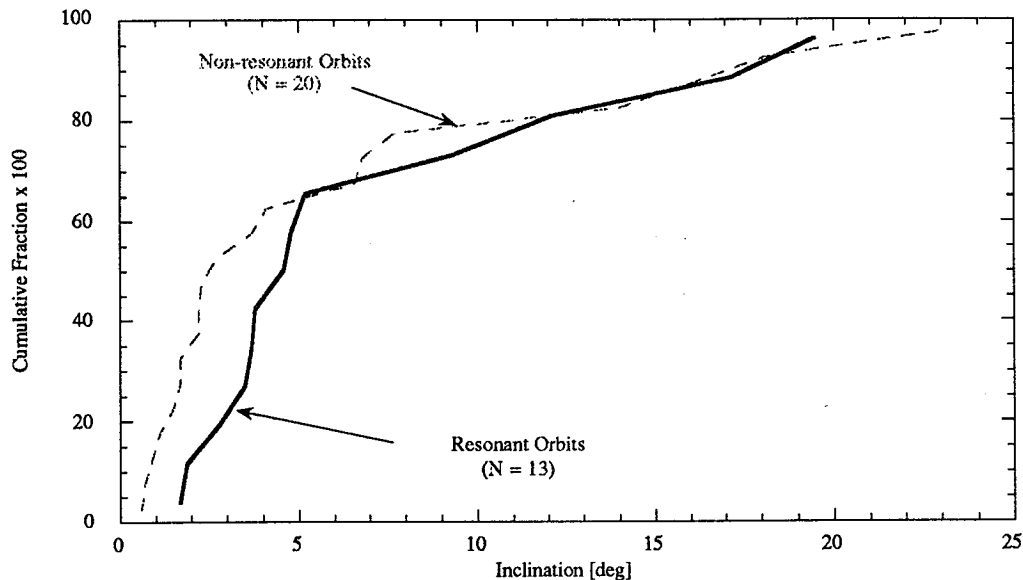


Figure 3 The number of objects having orbital inclination $\geq i$ is plotted as a function of i . The dashed and solid curves show objects having resonant and non-resonant (mostly 3:2) orbits, respectively.

- Escapees from the Kuiper Belt may drift to the inner solar system and be observed as short-period comets. Objects in the intermediate dynamical stage are known as "Centaur". They are characterized by dynamical lifetimes of 10^6 to 10^7 years. The archetype is 2060 Chiron and, at the start of our work, only 3 Centaurs were known. We discovered 2 Centaurs in the course of our survey and concluded from this statistic that the surface density (and total population) of such

objects must be higher than the only extant prediction by a factor of 50 (*JLC96*). A source of Centaurs in addition to the Kuiper Belt may be required to account for the observed excess.

- The Kuiper Belt Objects are by and large too faint to permit detailed spectroscopic studies, even on telescopes such as the Keck. Instead, we used broadband optical colors to attempt to study the surface properties of these objects. The main result (Figure 4; *LJ96*) was our finding that the KBO surfaces exhibit a wide range of colors, from Chiron-like neutrality to extreme Pholus-like redness. This implies that the surfaces of Kuiper Belt objects are varied in nature. We suggested that color variations might result from the on-going competition between cosmic-ray reddening and stochastic collisional resurfacing. It is also possible that the different colors simply reflect different compositions, although we do not know how such compositional differences might be created.

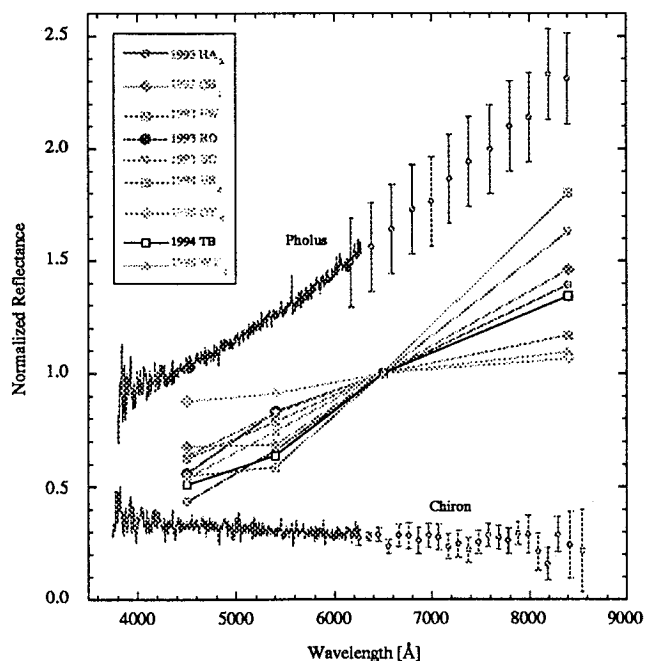


Figure 4 Colors of Kuiper Belt objects and Centaurs, determined from observations at the Keck and other telescopes (Luu and Jewitt 1996). A wide range of colors is observed implying a wide range of surface types.

- We attempted to popularize this research via a popular-level paper on the Kuiper Belt for the magazine *Scientific American*. In addition, numerous articles about the Kuiper Belt have appeared in the popular press in the past few years.

3 Personnel

This research constituted part the PhD thesis research of graduate student Jun Chen. Her PhD "Survey for Trojan Asteroids Beyond Jupiter" focussed on deep surveys of the outer solar system directed towards 1:1 resonant objects. She will graduate in the summer of 1997.

4 Major Publications

- D. C. Jewitt and J. X. Luu (1995), "The Solar System Beyond Neptune", *Astronomical Journal*, **109**, 1867-1876. *JL95*
- D. Jewitt, and J. Luu (1996). The Plutinos. For Completing the Inventory of the Solar System, Flagstaff meeting of the Astronomical Society of the Pacific, Summer 1994 .
- J. Luu and D. Jewitt (1996), "Reflection Spectrum of the Kuiper Belt Object 1993 SC", *Astron. J.*, **111**, 499-503.
- J. Luu and D. Jewitt (1996). "Color Diversity Among the Centaurs and Kuiper Belt Objects", *Astron. J.*, **112**, 2310. *LJ96*
- D. Jewitt, J. Luu and J. Chen (1996). "The Mauna-Kea Cerro-Tololo (MKCT) Kuiper Belt and Centaur Survey", *Astron. J.*, **112**, 1225-1238. *JLC96*
- J. Luu and D. Jewitt (1996). The Kuiper Belt. *Scientific American*, May 1996 issue (pp. 48-55).
- D. Jewitt and J. Luu (1996). "Kuiper Belt: The Solar System Beyond Neptune". Invited review for Asteroids, Comets, Meteors '96, held Versailles, France, July 8 - 12 1996. In press.
- D. Jewitt and J. Luu (1997). "The Kuiper Belt". Invited review for the Stardust to Planetesimals Symposium, held Santa Clara, California, June 24-26 1996. In press.